Advanced Numerical Methods for NWP Models

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LONG-TERM GOALS

The long-term goal of this research is to construct the Navy's next-generation global numerical weather prediction (NWP) model using new numerical methods specifically designed for distributed-memory and vector computers. To distinguish it from the current Navy global atmospheric model, the navy Operational Global Atmospheric Prediction System (NOGAPS), we shall refer to this new model as the Navy's Spectral Element Atmospheric Model (NSEAM). To take full advantage of distributed-memory computers, the spherical global domain of NSEAM is partitioned into local sub-domains, or elements, which can then be solved independently on multiple processors. The numerical methods used on these sub-domains must be not only local in nature but also high-order accurate and highly efficient. Thus, NSEAM is being constructed so that it is as accurate as the current spectral model (NOGAPS); is more efficient, thereby allowing for finer resolution forecasts; and is geometrically more flexible, thereby allowing for the use of adaptive or telescoping grids. This will allow for better coupling with mesoscale models and eventually perhaps allowing for a modeling paradigm whereby the global and mesoscale models are either unified or at least share the same numerical algorithms which facilitates their maintenance.

OBJECTIVES

The objective of this project is to construct new high-order local methods for the Navy's next-generation global NWP model. The high-order accuracy of these methods will ensure that the new model yields the same accuracy as the current spherical harmonics model while the locality of these methods will ensure that the efficiency of the model increases as the number of processors increases.

APPROACH

To meet our objectives we explore:

1. spectral element (SE) and discontinuous Galerkin (DG) methods on quadrilateral and triangular grids,
2. semi-implicit (SI) and semi-Lagrangian (SL) time-integrators,
3. adding the NOGAPS physics package to the NSEAM dynamics, and
4. the nonhydrostatic version of NSEAM.

The power of SE and DG methods is that they are high-order accurate, like spherical harmonics methods, yet are completely local in nature – meaning that the equations are solved independently

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within each individual element and processor. Furthermore, high-order methods have minimal dispersion error which is an important property for capturing fine-scale atmospheric phenomena (e.g., tropical cyclones, Kelvin and Rossby waves). In addition, SI and SL methods offer vast improvements in efficiency due to the longer time steps that they permit.

After validation of the SE, DG, SI, and SL discretization on barotropic test cases, the full 3D adiabatic (dry physics) hydrostatic primitive equation model was closely scrutinized. The SI time-integrator of NSEAM was ported to the message-passing interface (MPI). At this point direct comparisons with the current version of NOGAPS were made. Superior performance of NSEAM over NOGAPS then justified the further effort into taking the steps to make NSEAM the next operational NWP model. In order to accomplish the final objective, the following steps must be accomplished:

1. the NOGAPS physical parameterization package must be coupled with the NSEAM dynamical core,
2. non-reflecting boundary conditions need to be added to NSEAM in order to avoid spurious wave reflections emanating from the orography, and
3. development of the tangent linear and adjoint models of NSEAM to be used for both data assimilation and sensitivity studies.

After this point, the modeling system can be said to be complete. This year we have successfully integrated the NOGAPS physics into the NSEAM dynamics. However, so far we have only tested the physics with very simple initial conditions, such as the aqua-planet and Rossby-Haurwitz wave experiments – both of which do not use real data but rather simplified initial conditions. In order to be able to include real data, various input routines must be developed such as the climatological data (ground wetness, albedo, etc.) which we have developed for a previous version of NSEAM. The final step will include the construction of absorbing boundary conditions, as well as tangent linear and adjoint models.

WORK COMPLETED

NSEAM Numerics. The main accomplishments in numerics this year involved the development of a new class of diagonal mass matrix triangular spectral element method (see Ref.[1]). Before this work, SE methods were only used on quadrilaterals and if they were used on triangles they did not possess a diagonal mass matrix which is the key to the efficiency of the SE method. With this new technology, we have built shallow water models on the sphere and we now propose to include this triangular SE method within the existing version of NSEAM with little modification to the model.

Physical Parameterization. The majority of the time this year was spent on coupling the NSEAM dynamical core with the current NOGAPS physical parameterization routines (called DIABAT). During FY2006 two separate approaches were used to couple the NSEAM dynamics with the NOGAPS physics. First, a single-column model (SCM) version of the NOGAPS physics was placed inside of NSEAM. This was a proof-of-concept approach to show that the NOGAPS physics would work "out of the box" within NSEAM. With this approach, we performed the aqua-planet experiment and our results compared quite favorably with those found in the literature. However, this approach proved too costly to use in an operational setting and a second approach was devised.

In the current approach, the NOGAPS physics routine (DIABAT) was removed from NOGAPS, minimal modifications were made, and then installed directly into NSEAM. The results so far have been quite impressive. The simple experiments run with this full model have shown to yield physically realistic results and the cost between the physics and dynamics is roughly one-to-one, which is what one would hope. We are now ready to tackle the aqua-planet and Madden-Julian Oscillation (MJO) experiments with this new model. The main advantage of this approach is that any changes made to the NOGAPS physics can be readily included into NSEAM. We now propose to compare the efficiency of NSEAM with NOGAPS physics to the NOGAPS system. Since the cost between physics and dynamics is roughly one-to-one this then means that NSEAM will continue to scale far better than NOGAPS, as the dry dynamics tests indicated previously.

An important issue raised when we coupled the NOGAPS physics with the NSEAM dynamics is the creation of noise in the precipitation fields along the element boundaries of the spectral elements. This is not an unexpected phenomenon but, nonetheless, it is a situation that must be rectified. In order to control this "spectral rain" we have developed sophisticated diffusion operators for the spectral element method; this is in fact a new area of research within the spectral element community and we have made great advances in creating these required high-order diffusion operators. If we use 2nd order diffusion, then the fields are too damped with little regard for the low frequency (long) waves. However, if we apply 4th order or higher hyper-viscosity, then we are guaranteed to keep the low frequency waves untouched. Regardless of which diffusion operator we use, we can now eliminate the effects of the so-called "spectral rain". A paper on this topic is in preparation.

RESULTS

<u>NSEAM Numerics</u>. At the present time, all spectral element models use quadrilateral elements for partitioning the grid. Quadrilaterals have worked very well in the past but they are not as geometrically flexible as triangles. The issue with triangles is that no one had yet devised a high-order (spectral element) triangular element approach that has the same high efficiency of quadrilateral-based spectral elements. We have developed a "true" triangular spectral element method. The advantages of using triangular elements is that we can now discretize the domain emphasizing specific regions of interest.

Figure 1: New class of adaptive unstructured grids possible wit the triangular spectral element method.

In Figure 1 we show an adaptive unstructured grid where the grid has been refined such that high resolution is obtained on the land masses and lower resolution along the oceans. However, we could also reverse the situation and obtain high resolution near specific regions of the oceans, for example, in order to track tropical cyclones more accurately. In Figure 2, we show the convergence rate of the new triangular spectral element method. For a method to be considered spectral, the method must converge at a rate of (N+1). In other words, for a fixed polynomial order, N, the error must decrease as a power of (N+1) when we add more elements. This is the rate of convergence that is reported in Figure 2. Note that for all orders of N we can indeed see that the order is between N and N+1. We expect to use the N=6 which is a sixth order polynomial that achieves roughly seventh order accuracy. We chose this value because in Ref. [1] we show that this value yields the highest accuracy for the lowest computational cost.

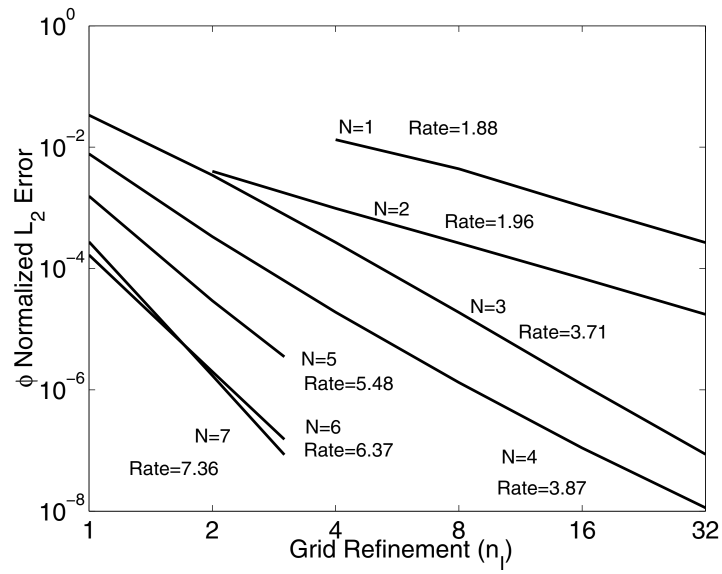
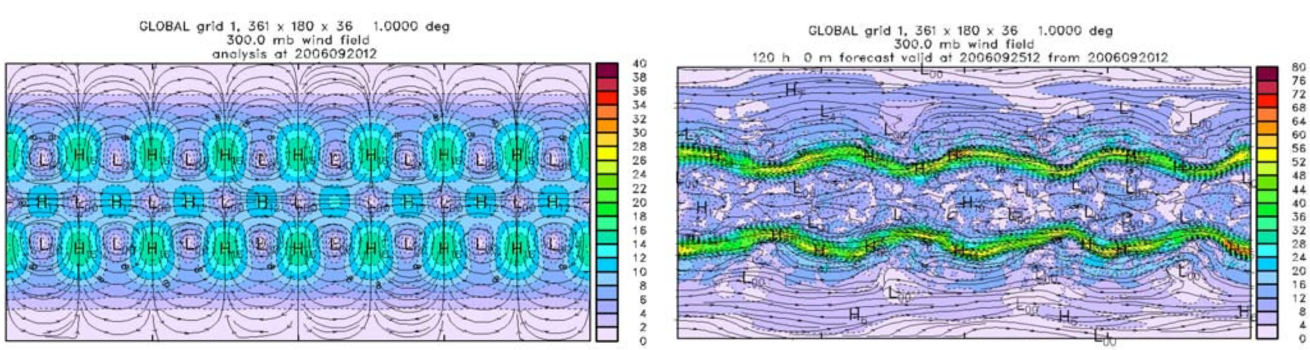


Figure 2: The convergence rate of the new triangular spectral element method. This shows that the method does indeed converge at an exponential (spectral) rate.

Physical Parameterization.

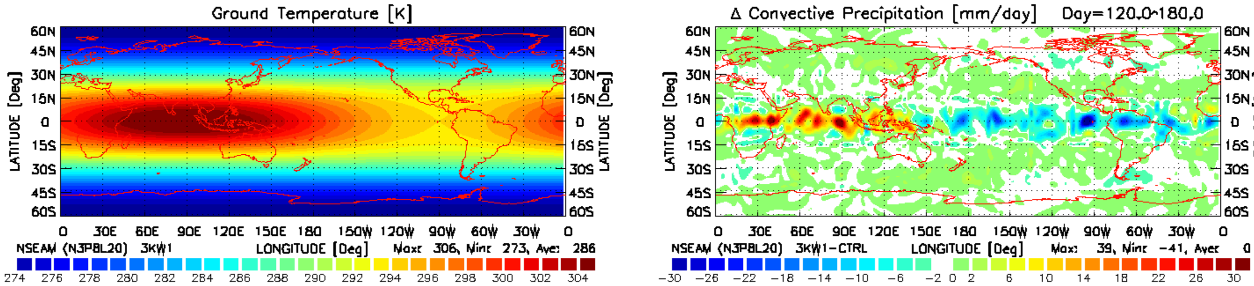
In order to validate whether the NSEAM dynamics run with NOGAPS physics is working properly, we ran the Rossby-Haurwitz wave number 4. For pure (dry) dynamics, NSEAM maintains the wave 4 structure indefinitely (up to at least 30 days). However, when the NOGAPS physics is added, the dynamics of the wave changes quite drastically.



a) Initial Time ***b) 5 Days***

Figure 3: 300mb wind.

In fact, we can see that at 300 mb (Figure 3) the wind field develops a very strong jet. This simple test confirms that the dynamics and physics are working well together to produce physically realistic results.



a) Surface Temperature Forcing ***b) Convective Precipitation***

Figure 4: The surface temperature and resulting convective precipitation for NSEAM dynamics with NOGAPS physics for the Aqua-Planet Experiment. The model was run successfully for a 3 year simulation but here we only show results after 6 months.

In a second test, we run the aqua-planet experiment. This experiment uses a specified sea-surface temperature as the forcing mechanism which then drives the planetary climate. This sea-surface temperature is shown in Figure 4a. This forcing eventually causes precipitation to occur near the equatorial region. The convective precipitation averaged over days 120 to 180 are shown in Figure 4b. These results, along with other detailed results such as Hough-Moeller and Wheeler-Kiladis diagrams (see Ref. [8]), show the generation of Rossby and Kelvin waves which suggests that the dynamics and physics are interacting properly.

IMPACT

NOGAPS is run operationally by FNMOC and is the heart of the Navy's operational support to nearly all DOD users worldwide. This work targets the next-generation of this system for massively parallel computer architectures. NSEAM has been designed specifically for these types of computer architectures while yielding the same high-order accuracy as NOGAPS.

TRANSITIONS

Improved algorithms for model processes will be transitioned to 6.4 (PE 0603207N) as they are ready, and will ultimately be transitioned to FNMOC with future NOGAPS upgrades.

RELATED PROJECTS

Some of the technology developed for this project will be used immediately to improve the current spectral transform formulation of NOGAPS in other NRL projects.

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